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Pseudocanalizing propagation with hyperbolic surface waves

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Abstract: Negative magnetic permeability allows for reversed phase propagation in HMMs. However, magnetic properties are difficult to realize in the visible wavelengths. We propose a similar effect for surface waves without requiring magnetic properties. © 2018 The Author(s)

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1. Introduction

Hyperbolic metamaterials (HMMs) are anisotropic structures, where the components of the diagonal (effective) permittivity tensor have opposing signs. In effect, the medium behaves as a metal in one direction, while exhibiting dielectric properties in the other direction. This leads to many peculiar properties, among which is the ability to carry electromagnetic waves with arbitrarily high wave vectors. Propagation of these high- k waves in HMMs is important for applications in superresolution imaging (*hyperlens*) [1] for example.

A dark-field hyperlens concept has been proposed [2, 3] to enable subwavelength imaging of weakly scattering objects as well. However, the design in Ref. [3] imposes conflicting requirements on HMM parameters and therefore a compromise between image quality and image contrast is required. Recently we discussed [4] a possible improvement of the design (the *pseudocanalization regime*) by incorporating HMMs with negative magnetic permeability. The magnetic properties enable to manipulate phase propagation in the medium, allowing for more freedom for choosing the material parameters and allowing to optimize for both image quality and image contrast.

Implementing magnetic properties in the visible spectrum is challenging, making it difficult to realize a feasible design for the pseudocanalization effect in the HMMs. As an alternative approach we show that surface modes in two- and three-layer systems also offer strong control over phase propagation. Here the phase propagation is controlled by structure of the multilayer system, so that no magnetic properties are necessary (i.e. $\mu = 1$).

2. Results and discussion

A single interface between two isotropic media can support a surface mode, given that the condition $-\epsilon_1 > \epsilon_2$ is fulfilled — as can be the case on a metal-dielectric interface, for example. To obtain hyperbolic surface waves we consider a system where the first layer is anisotropic, i.e. it is given by anisotropic permittivity tensor $\hat{\epsilon}_1 = \text{diag}(\epsilon_o, \epsilon_e, \epsilon_o)$. We note that by imposing condition $\epsilon_o < -\epsilon_2 < \epsilon_e$ we have a system where a propagating surface mode exists in one direction but not the other, which is analogous to a bulk waves in a HMM.

To reverse phase propagation for the hyperbolic surface waves, we extend the results by Shin et al [5]: they studied isotropic surface modes in two- and three-layer systems and showed that in a metal-dielectric-metal system the phase velocity is antiparallel to the propagation direction (i.e. the phase propagation is reversed). In our case we choose to have anisotropic metal - dielectric - isotropic metal system, with permittivities $\hat{\epsilon}_1 = \text{diag}(\epsilon_o, \epsilon_e, \epsilon_o)$, ϵ_2 and ϵ_3 respectively. By imposing suitable conditions for the permittivities, we can obtain a hyperbolic surface mode, which exhibits reversed phase propagation direction.

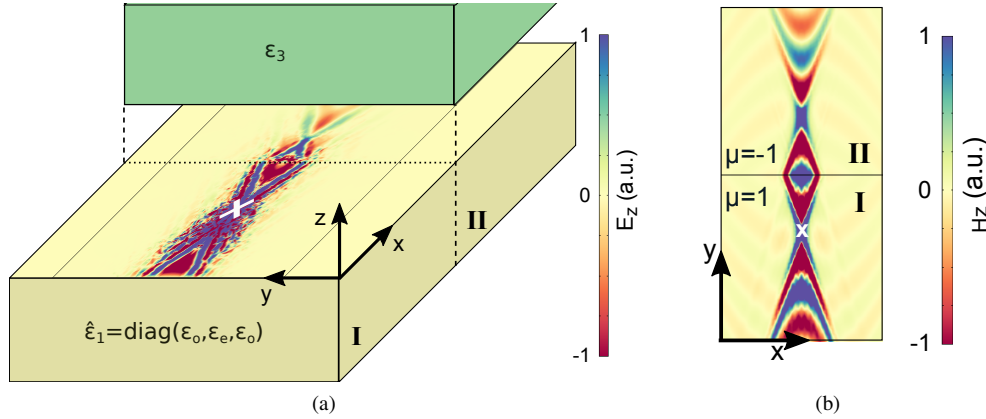


Fig. 1: (a) Geometry of the system, showing region with positive (I) and negative phase propagation (II). Material parameters are for (I) $\epsilon_o^{(I)} = -3$, $\epsilon_e^{(I)} = -1$ and for (II) $\epsilon_o^{(II)} = -1$, $\epsilon_e^{(II)} = -6$ and $\epsilon_3^{(II)} = -1.5$. The dielectric layer is $\epsilon_2 = 2$ for both cases. (b) Comparable system for bulk waves in HMM, where $\epsilon_o^{(I)} = -12$, $\epsilon_e^{(I)} = -1.33$ and $\epsilon_e^{(II)} = -1.33$, $\epsilon_e^{(II)} = 12$. For both figures a point source is indicated with white cross.

Combining the two- and three-layer regions leads to the system shown in [fig. 1a](#). The two-layer region supports hyperbolic surface waves with normal phase propagation direction (corresponding to bulk waves in normal HMM). The hyperbolic surface modes in the three-layer region however exhibit negative phase velocity, corresponding to bulk waves in a μ -negative HMM. For comparison, we show in [fig. 1b](#) a comparable HMM system, where a μ -negative medium is used to reverse the phase propagation of bulk waves.

To summarize, we have shown that anisotropic multilayer systems support hyperbolic surface modes with both positive and negative phase propagation. This allows to design structures that enable surface waves analogue to the pseudocanalization effect in bulk HMMs. As the system is relatively flexible with regards to electromagnetic properties, we expect it to be feasible to design structures suitable for fabrication and experimental characterization. Although the proposed design still requires strong anisotropy not available in natural materials, it is possible to fabricate meta-material structures giving the strong permittivity needed [6, 7].

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